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STUDY OF SOLID ROCKET MOTORS FOR A SPACE SHUTTLE BOOSTER

FINAL REPORT

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ENVIRONMENTAL IMPACT STATEMENT
SOLID ROCKET MOTOR
SPACE SHUTTLE BOOSTER

United Technology Center DIVISION OF UNITED AIRCRAFT CORPORATION

CAT. 28

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA

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1.0 PROGRAM DESCRIPTION

The NASA Space Shuttle Program will provide the Nation with the capability of transporting payloads into earth orbit at low cost. The space shuttle will consist of a booster stage and an orbiter which carries the space crew and payload. The booster will transport the orbiter until it reaches a speed from which it can accelerate under its own power to the desired orbital velocity. The orbiter, having discharged its payload in orbit and taken on cargo and crew for return to earth, will reenter the atmosphere and fly to its destination where it will be readied for another shuttle flight.

At some time in the future the booster stage also, upon completing the launch of an orbiter, will fly back to its ground station and be made ready for another flight. However, since the simultaneous design and development of a reusable booster and a reusable orbiter will require a relatively long time and probably demand more resources than the Nation can make available in view of other priorities, NASA has decided to concentrate on the development of the reusable orbiter and to postpone that of a reusable booster stage.

Thus, the booster stage to be used during the first years of space shuttle operation will be jettisoned on burnout, and the hardware will be dropped or lowered into the ocean and partially or totally recovered. For this stage, NASA is considering the use of clusters of solid propellant motors similar to the two Stage 0 motors of the Titan III-C system. These motors are fully man rated and have a record of 19 flights without any failure.

No final design of a solid propellant booster stage has yet been selected, but from an environmental viewpoint, only a limited number of parameters are of significant importance. Of the various combinations and configurations of 120- and 156-in.-diameter motors under consideration, one configuration has the highest pollution potential because it utilizes the largest total amount of propellant and also gives the largest mass flow of exhaust products per second. This configuration is considered in this statement; it is a booster stage consisting of six seven-segment, 120-in.-diameter (UA 1207) motors with a combined propellant weight of 3.6 million pounds, a burning duration of 135 sec, and a sea level thrust of nearly 7 million pounds, providing an initial acceleration of 1.28 g.

It is further assumed that the launch rate will be 60 or less per year, and that no launch will follow another within less than a few hours. All launches are assumed to take place at the Kennedy Space Center in Florida. The environmental impact of static preliminary flight rating test firings of a series of 156-in.-diameter motors at the UTC Development Center at Coyote, California, will also be discussed.

2.0 ATMOSPHERIC POLLUTION

During operation of the space shuttle booster stage, propellant combustion products are ejected into the atmosphere. Table I lists the exhaust composition which remains constant during the whole burning time and will be largely unaffected by minor propellant changes under consideration. Omitted from the table are the products present in the exhaust in trace quantities only; these do not include any material that could have a toxic or other pollution effect in such small concentrations.

TABLE I
EXHAUST COMPOSITION

Exhaust Product	Mass Fraction (all products)	Mole Fraction (gas)
Al_2O_3	0.304	–
CO	0.280	0.28
HCl	0.207	0.16
N_2	0.084	0.08
H_2O	0.068	0.11
CO_2	0.028	0.02
H_2	0.025	0.35
$FeCl_2$	0.004	–
	1.000	1.00

The solids, alumina and iron salt, occur in natural dust arising from the weathering of rocks, and they are formed in particle sizes which are also typical of dust. The gases can be found as natural constituents in the earth's atmosphere. However, dust and two of the gases, CO and HCl, can have adverse effects on man, animals, or vegetation if the concentration in the atmosphere is excessive. The dispersion of these constituents in the atmosphere will therefore be examined.

2.1 DISPERSION OF EXHAUST PARTICLES AND GASES FROM LAUNCH

The exhaust gases produced during launch of the booster stage leave the nozzle at a velocity of 8,000 ft/sec and at a stagnation temperature of 5,500°F. The gases initially swirl about the launch

platform, mixing with the surrounding air and forming the so-called ground cloud. The formation and further behavior of the ground cloud are reasonably well understood and predictable, based on analysis and photographic observation of Titan III-C launches. The momentum of the exhaust gases is rapidly dissipated in turbulent eddies which mix the exhaust gases with large quantities of air. As the vehicle rises from the pad, the momentum of the ejected gases still carries them into the ground cloud, although their buoyancy slows their downward motion. Twenty-two seconds after ignition the vehicle has reached an altitude of 2,300 ft, from which its exhaust gases no longer reach the ground cloud but instead form the typical skyward trail. Table II shows the total quantity of each major exhaust product contained in the ground cloud. The data are calculated for the series burn configuration, which utilizes the most solid propellant. The radius of the ground cloud will reach 710 ft., and the mass fraction of the exhaust products in it is only 0.0058.

TABLE II
MATERIAL RELEASED INTO GROUND CLOUD

Exhaust Product	Pounds Per Launch
Al_2O_3	204,000
CO	187,000
HCl	139,000
N_2	56,300
H_2O	45,500
CO_2	18,800
H_2	16,700
$FeCl_2$	2,700
	670,000

The mean temperature of the gases in the cloud has dropped mainly because of the added air, but it is still approximately 35°F above that of the surrounding air. The cloud, therefore, rises until at some altitude its temperature, which continues to drop by mixing with additional air and by adiabatic expansion, becomes equal to that outside. This terminal altitude will vary greatly with atmospheric conditions on the day of launch. Under isothermal conditions, the center of the cloud will reach 2,600 ft. Since, however, the environmental impact will be greatest when the cloud rises to the least altitude, there will here be assumed a very stable atmosphere, corresponding to a strong ground-based temperature inversion, which allows the center of the cloud to rise only to 1,330 ft.

Such strong inversions occur rarely, if ever, at the Kennedy Space Center. The cloud now has a radius of 916 ft, and the original exhaust gases constitute only 0.27% of its mass. The mean concentration of CO, assuming no combustion or other chemical processes have taken place to remove this gas, is 790 ppm; that of HCl is 450 ppm. The process up to this point was driven by energy derived from the rocket combustion process.

The cloud, at its terminal altitude, now begins to drift downwind, increasing in size by turbulent mixing with surrounding air and eventually reaching back to the ground. Applying standard methods for the calculation of atmospheric diffusion from an elevated source used by the Environmental Protection Agency and the Atomic Energy Commission, and taking the adverse case of a very stable atmosphere which led to a low cloud height, where the cloud reaches the ground it may have at most an HCl concentration of 3.7 ppm, a CO concentration of 6.5 ppm, and four 10μ alumina particles per cubic centimeter. This last number is similar to the concentration of particles in dusty air, and the exposure, which will be of the order of minutes, is so short that the alumina produced during the firing can be considered negligible as a pollutant. The exposure to CO is well below Federal air quality standards which permit up to 35 ppm for one hour, and therefore also negligible. Only HCl remains to be considered.

Factors exist which make it unlikely that the HCl concentrations and exposure quoted will actually be reached. There are at present no good data on the fate of HCl in the atmosphere, and the calculations so far have conservatively assumed that it remains unaltered in the atmosphere as a gas. However, HCl is reactive, extremely hygroscopic, and highly soluble in water. If any liquid water is present, or in fact if the relative humidity is above 75%, the HCl will be absorbed by water droplets and removed from the atmosphere. HCl is also removed by soil, and it adsorbs on the surfaces of airborne particles and may react with their constituents. Further research may show that still other mechanisms remove HCl from the atmosphere.

In view of the uncertainties discussed, it is of interest to note that the maximum ground level HCl concentration predicted for the space shuttle booster is only 60% greater than for the operational Titan III-C boosters calculated with the same analytical model and meteorological parameters. Although the space shuttle booster releases into the ground cloud a quantity of HCl that is five times larger, this is largely offset by the greater buoyancy of the ground cloud which takes it to a higher altitude. In 17 Titan III-C launches from the Kennedy Space Center under a variety of weather conditions with on-shore as well as off-shore winds, no adverse environmental effects have ever been observed or reported. It can, therefore, be concluded that none would be expected from repeated launching of a solid propellant space shuttle booster.

Some designs for smaller space shuttle booster stages provide for the parallel burning of the main orbiter propulsion unit during launch. Since the total thrust at launch will not be greatly changed, the overall pollution remains the same. The HCl introduced by the solid rocket motors is reduced because fewer motors are used while the orbiter engines contribute no HCl. The tendency of water to condense in the ground cloud is not significantly affected.

2.2 POLLUTION EFFECTS OF HCl

The chloride ion occurs in the metabolism of plants, animals, and man and is, therefore, not considered toxic. However, chlorine and most of its compounds (including kitchen salt) have adverse effects if ingested in too high concentrations.

Because of its hygroscopicity, some HCl gas in the atmosphere will be absorbed by the moist tissues of the eye and by the respiratory tract. If the amount is small there are no effects. As the amount increases the tissues involved are irritated; a typical response is coughing. With increasing severity the distress can mount, causing inflammation, pain, and other symptoms. When the irritation has not been overly severe or prolonged there is no effect on health.

The limits which various health authorities have set for permissible concentrations of HCl in air vary considerably. The Committee on Toxicology of the National Academy of Science/National Research Council, has recently proposed a Short Term Public Limit of 4 ppm, which is set below the level of irritation that may lead to significant discomfort and presents no health hazard. The Public Emergency Limit, which requires that there be no adverse health effect but recognizes the possibility of some temporary discomfort, is set at 7 ppm for short exposures. The impact of this concentration may be no more than strong odor or, at the most, slight irritation of the mucous membranes.

The concentration of 3.7 ppm, calculated for an adverse case to which a downwind population could be exposed, is safely below the limit at which only slight irritation would be felt. The total dosage is also likely to be below the Surgeon General's limit of 120 ppm-min for uncontrolled populations, and will not remotely approach the industrial limit of 2,400 ppm-min. Because of the meteorological uncertainties pointed out in the previous section, it is of precautionary interest to know what happened in laboratory experiments when the permissible HCl concentration limits and dosages were greatly exceeded. Two separate investigators using cats, rabbits, and guinea pigs reported the expected irritation but no after effects of exposures at 100-ppm HCl and more for up to 6 hr, and at 70-ppm HCl for five daily consecutive 6-hr periods. It is, therefore, concluded that the HCl content of the ground cloud constitutes no hazard to humans or animals under any condition.

No effect on vegetation of HCl in the atmosphere at such low concentrations is known to occur for exposures less than several hours long. However, if the atmosphere is high in humidity and it begins to rain, the acidity of the rain water due to dissolved HCl may affect the appearance of sensitive surface areas of leaves. However, the HCl would quickly wash out or be removed by the sap flow. Any other effects that acidity of atmospheric moisture can have are precluded by the low concentration of HCl, the very short exposure time after each launch, the low exposure rate, and the low probability of precise repetition of all meteorological conditions at several launches.

In summary, HCl contained in the ground cloud resulting from each space shuttle launch does not constitute a significant pollution problem even under the most extreme conditions. It is recognized that much better knowledge of the fate of rocket-emitted HCl in the atmosphere should be obtained, since this may further alleviate any concern regarding this exhaust product.

2.3 DISPERSION OF EXHAUST PARTICLES AND GASES FROM TEST FIRINGS

The test firings of solid propellant motors of the type to be used in the space shuttle booster stage involve only single motors. The particular booster stage configuration considered so far utilizes only UA 1207 motors; however, other configurations may use 156-in.-diameter motors which, as single units, contain a greater amount of propellant and therefore emit more potential pollutants. The static firings of these larger motors are considered here as they are conducted in the upward firing vertical test stands at the UTC Development Center.

Compared to the ground cloud formed during a launch, the cloud formed as a result of a test firing benefits from the direction of the exhaust gas flow and from the absence of the heat loss arising from contact of the gases with the ground. Moreover, while only the exhaust products emitted during the first seconds of a launch become part of the ground cloud, in a static test the cloud contains all exhaust products from the whole firing. It therefore has a much greater volume and contains much more heat, and in rising it ascends to far greater heights. Calculations for a UA 1207 motor show that even in a very stable atmosphere the height of the top of the cloud will be of the order of 9,000 ft above the test site. In two test firings of such motors, heights of 9,700 and 11,300 ft were actually measured. For all practical purposes, no gaseous portion of a cloud at this height descends to ground level before it has been dispersed to the point of being unidentifiable. The potential ground level effects of HCl, which had to be considered for ground clouds from launches, are nonexistent for test firings.

A 156-in.-diameter motor may contain as much as 1.25 million pounds of propellant, more than twice as much as a UA 1207 motor. The cloud will have nearly twice the volume, however, and the HCl concentration will be about the same. The cloud will rise about 2,000 ft more and will, therefore, have no environmental impact.

Leaf damage to a vegetable crop from raindrops containing HCl is precluded by the climate of the test site where precipitation occurs on an average of only 16 days per year. No large motor firings are carried out on such days.

2.4 GLOBAL POLLUTION

The quantities of all materials emitted by space shuttle boosters within the troposphere (up to 40,000 ft) are insignificant compared to the same or similar materials continually added from other, natural or human, sources and purged by natural processes. It is not immediately obvious whether this will also be true in the stratosphere. Table III shows the amounts of exhaust products which are ejected from 40,000 ft to burnout at 135,000 ft.

TABLE III

MATERIAL RELEASED INTO STRATOSPHERE
(Between 40,000 and 135,000 ft)

Exhaust Product	Pounds per Launch	Tons per Year (60 Launches)
Al_2O_3	468,000	14,000
CO	431,000	12,900
HCl	319,000	9,550
N_2	129,000	3,880
H_2O	105,000	3,140
CO_2	43,000	1,290
H_2	39,000	1,150
$FeCl_2$	6,000	190
	1,540,000	46,100

The value of 14,000 tons of Al_2O_3 for 60 launches compares with a flux of extraterrestrial particles toward the ground estimated at 10^7 tons/year and is, therefore, insignificant. Moreover, the Al_2O_3 particles with a median diameter of 10μ or greater will settle very rapidly in terms of meteorological processes in the stratosphere. The gases that are normal ingredients of the atmosphere are also emitted in quantities too small to have any significant effect, but no good basis exists to predict the effects, if any, of HCl. If it is distributed evenly throughout the stratospheric air mass in this altitude band, the quantity injected in 60 launches would lead to a concentration of 7×10^{-6} ppm, which is very small compared to the ozone concentration of 10 ppm and can have only a negligible effect on the spectral absorption properties of the atmosphere. Also, the particle flux earthward is likely to adsorb and scavenge HCl. If it is considered that even the tenous upper atmosphere is quite massive and quickly purges itself of new material released in it, it may safely be assumed that a readily adsorbed and highly reactive material like HCl present in relatively small quantities will not survive long enough to have any noticeable effect.

3.0 NOISE

The space shuttle booster produces loud noise during its operation, which has its only environmental impact during launch since in flight the increasing distance rapidly attenuates the sound reaching the ground.

All rockets launched at the Kennedy Space Center have produced such noise, and appropriate acoustical boundary limits have been set. The highest sound pressure levels have occurred during Apollo launches. Compared to the Saturn V booster the space shuttle booster stage will give nearly the same sea level thrust and a slightly greater mass flow rate of exhaust gases at launch. However, the specific impulse of the propellant used in the UA 1207 space shuttle booster motors is 12% lower than that of the F-1 Apollo booster propellant; as a consequence, the exhaust gas velocity also is 12% lower. The sound pressure produced by gas jets, other parameters being equal, is a very high power function of the gas velocity. This means that the highest sound level measured within the Kennedy Space Center controlled area, which was 128 db during the first eight Saturn V launches, will be reduced to 124 db during a space shuttle launch. At the nearest urban area, Titusville, the sound will be attenuated to 113 db instead of 117 db for Apollo. These sound levels, occurring for periods of seconds only, are well within the range of those to which a population is habitually exposed by jet planes, motorcycles, and other equipment.

At the UTC Development Center, only single motors are fired in static tests. Four UA 1207 motors and eight UA 1205 motors, whose sound pressure output is about the same, have already been test fired. The remoteness and nature of the terrain preclude the sound directly impinging on any populated area, and at the boundary of UTC's property in the direction of the nearest urban area, 13,000 ft away, the maximum reading during a UA 1207 motor test was 95 db. UTC has never received a noise complaint. A 156-in.-diameter motor with its higher thrust will give a sound pressure about 3 db higher, which is a barely noticeable difference.

Under certain meteorological conditions the sound of the test firing of a large motor can be heard over a wide area including some densely populated cities. While the noise level is quite low at these distances, the long (2-min) duration of the sound has occasionally given rise to concern about the cause and inquiries to civil authorities. UTC, therefore, as a matter of policy arranges for the announcement by local newspapers and radio stations of forthcoming large-motor firings.

4.0 SUMMARY

During any vertical rocket launch the exhaust products ejected during the first part of the firing collect in a ground cloud which rises due to its buoyancy and drifts downwind. The cloud grows by turbulent mixing with air and eventually can reach down to the ground again. In the case of a space shuttle booster stage composed of solid propellant rocket motors burning in parallel or in series with the orbiter propulsion unit, calculation of the degree of dilution with air at the point where the ground cloud touches the ground indicates that the only potentially harmful pollutants, CO and HCl, will be too diluted to constitute a hazard. Their concentrations will be little higher than those formed during Titan III-C launches which have never posed a ground pollution problem.

The mass of products ejected during a launch within the troposphere is insignificant in terms of similar materials that enter the atmosphere from other sources. This is also the case within the stratosphere, even when a maximum launch rate is assumed.

In respect to noise, the space shuttle booster stage will produce a slightly lower sound pressure level than a Saturn V booster.

At UTC's California test site the test firing of single motors produces no ground cloud and presents no pollution or noise problems.